

# Search for Excited and Exotic Muons at CDF

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**Abstract.** We present a search for the production of excited or exotic muons ( $\mu^*$ ) via the reaction  $\bar{p} + p \rightarrow \mu^* + \mu \rightarrow \mu\gamma + \mu$  using  $371 \text{ pb}^{-1}$  of data collected with the Run II CDF detector. In this signature-based search, we look for a resonance in the  $\mu\gamma$  mass spectrum. The data are compared to standard model and detector background expectations, and with predictions of excited muon production. We use these comparisons to set limits on the  $\mu^*$  mass and compositeness scale  $\Lambda$  in contact interaction and gauge-mediated models.

**Keywords:** excited, exotic, muon

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## INTRODUCTION

In the standard model (SM), quarks and leptons are considered fundamental particles. An indication that quarks and leptons are composite particles would be the observation of their excited states [1]. Additionally, when the standard model is embedded in larger symmetry groups, exotic fermions are predicted [2]. We search for singly produced excited and exotic muons where the  $\mu^*$  decays in the  $\mu\gamma$  channel, resulting in a  $\mu\mu\gamma$  final state signature. The  $\mu\mu\gamma$  signal is fully-reconstructible with low background expectation.

## EXCITED AND EXOTIC MUON MODELS

We consider two models for excited and exotic muon production: a contact interaction (CI) model and a gauge mediated (GM) model. In the CI model, excited muon production is described by a four-fermion Lagrangean of quarks to excited and SM muons [1]. The CI cross sections depend on the  $\mu^*$  mass  $M_{\mu^*}$  and compositeness scale  $\Lambda$ . The CI process is modeled by PYTHIA [3]. The production of  $\mu^*$  in the GM model is described by its coupling to gauge bosons [4]. The GM cross sections depend on  $M_{\mu^*}$  and  $f/\Lambda$ , where  $f$  is a phenomenological coupling constant. The programs LANHEP [5] and COMPHEP [6] are used to calculate leading order GM cross sections and generate GM events. For both models, the  $\mu^*$  decays are prescribed by the GM Lagrangean [7].

## DATASET AND SIGNAL SELECTION

We use  $371 \text{ pb}^{-1}$  of data collected with the high  $p_T$  muon trigger at CDF from February 2002 through September 2004. We search for events consisting of two muons and a photon. The isolated muons must have  $p_T > 20 \text{ GeV}/c$  and be located in the central portion of the detector ( $|\eta| < 1$ ), with at least one detected in the muon chamber. Muons are identified by their minimum-ionizing particle properties. The isolated photon must have  $E_T > 25 \text{ GeV}$ , can be located in the central or forward region, and is identified by its electromagnetic shower properties. In addition, we veto events with  $81 < M_{\mu\mu} < 101 \text{ GeV}/c^2$ , to remove events produced by initial-state radiation (ISR)  $p + \bar{p} \rightarrow Z + \gamma$ .

## TOTAL SIGNAL ACCEPTANCE

The total signal acceptance is measured using the GEANT[8]-based CDF detector simulation. The CI total signal acceptance increases from 13% at  $M_{\mu^*} = 100 \text{ GeV}/c^2$  to an asymptotic value of 21% for  $M_{\mu^*} > 400 \text{ GeV}/c^2$ . For the

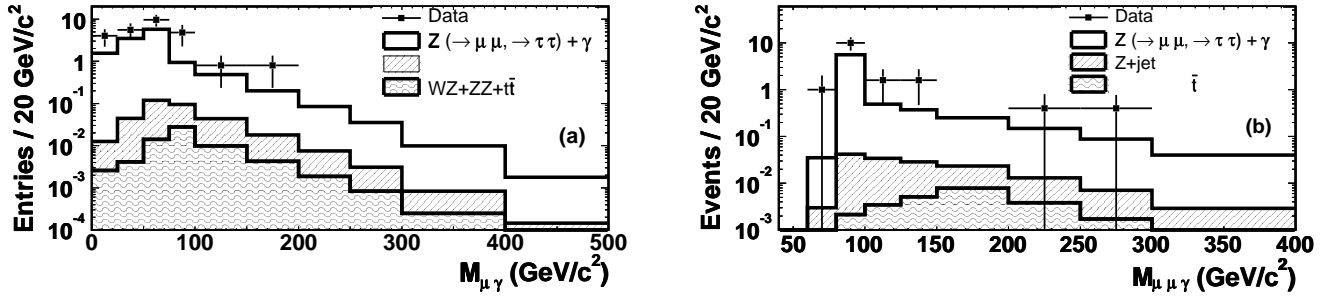


FIGURE 1. Background predictions and data observations for  $M_{\mu\gamma}$  (a) and  $M_{\mu\mu\gamma}$  (b).

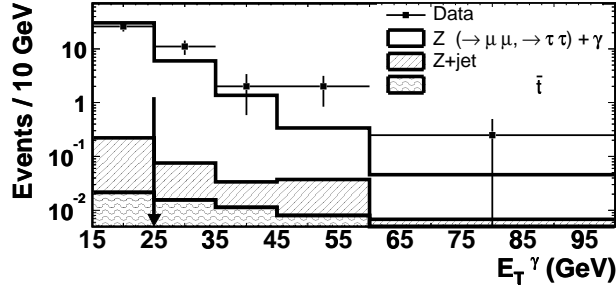


FIGURE 2. Background predictions and data observations for photon  $E_T$ .

GM model, the total signal acceptance increases from 12% at  $M_{\mu^*} = 100$  GeV/c<sup>2</sup> to 23% for  $M_{\mu^*} > 300$  GeV/c<sup>2</sup>.

## BACKGROUND ESTIMATES AND DATA OBSERVATIONS

The  $\mu\mu\gamma$  signature can be produced by several standard model and detector sources: (1)  $Z/\gamma^*(\rightarrow \mu\mu) + \gamma$ ; (2)  $Z/\gamma^*(\rightarrow \tau\tau) + \gamma$ ; (3)  $Z(\rightarrow \mu\mu) + jet$ , where a jet is misreconstructed as a photon; (4)  $t + \bar{t} \rightarrow \mu\nu\mu\nu b\bar{b}$ , where a fermion radiates a high- $E_T$  photon; (5)  $W(\rightarrow e\nu) + Z(\rightarrow \mu\mu)$  and  $Z(\rightarrow ee) + Z(\rightarrow \mu\mu)$ , where an electron is misidentified as a photon. The primary background  $Z/\gamma^*(\rightarrow \mu\mu) + \gamma$  is modeled using the ZGAMMA program [9]. The  $Z(\rightarrow \mu\mu) + jet$  is estimated using data. The total background prediction is  $8.3 \pm 0.9$  events ( $16.6 \pm 1.8$   $\mu\gamma$  combinations). In our ISR  $Z + \gamma$  control region,  $81 < M_{\mu\mu} < 101$  GeV/c<sup>2</sup> and  $E_T^\gamma < 50$  GeV, we predict  $7.4^{+1.2}_{-0.8}$  and observe 5 events.

In the signal region, we observe 17 events with a background prediction of  $8.3 \pm 0.9$  events. The background prediction and data are shown as a function of  $M_{\mu\gamma}$  in Figure 1(a). Several studies were done to understand the observed excess. The  $Z \rightarrow \mu\mu\gamma$  background, where the  $\gamma$  is produced via final-state radiation (FSR), is defined by  $81 < M_{\mu\mu\gamma} < 101$  GeV/c<sup>2</sup>. In this region, we observe 11 events with a prediction of  $5.5 \pm 0.5$  events, as shown in Figure 1(b). As a check, we lower the  $E_T$  cut to 15 GeV and observe 43 events, with a prediction of  $38.5 \pm 4.0$  events, as shown in Figure 2. These studies indicate that the excess at low mass is consistent with an upward statistical fluctuation, primarily in  $Z \rightarrow \mu\mu\gamma$  FSR. There is no excess at high mass to indicate new physical processes.

## $M_{\mu^*}$ LIMITS AND EXCLUSION REGIONS

A Bayesian approach is used to obtain the upper limits on the experimental cross section at the 95% confidence level (C.L.). For  $M_{\mu^*} = \Lambda$  ( $M_{\mu^*} = \Lambda/f$ ) in the CI (GM) model, masses below 853 GeV/c<sup>2</sup> (221 GeV/c<sup>2</sup>) are excluded, as shown in Figure 3. Because the GM exotic muon cross section depends on both  $M_{\mu^*}$  and  $f/\Lambda$ , we plot the two-dimensional  $f/\Lambda - M_{\mu^*}$  exclusion region in Figure 4(a). The excited muon CI model is valid for  $M_{\mu^*}/\Lambda < 1$ ; we plot the CI exclusion region in the  $M_{\mu^*}/\Lambda - M_{\mu^*}$  plane in 4(b).

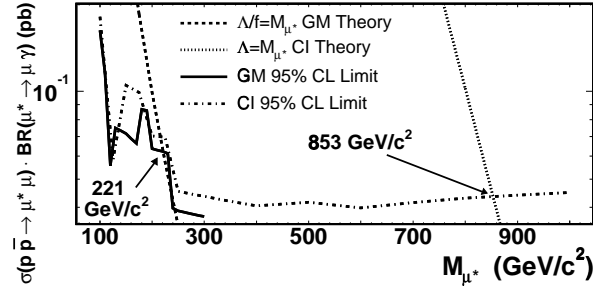


FIGURE 3. Mass limits for  $M_{\mu^*} = \Lambda$  ( $M_{\mu^*} = \Lambda/f$ ) in the CI (GM) model.

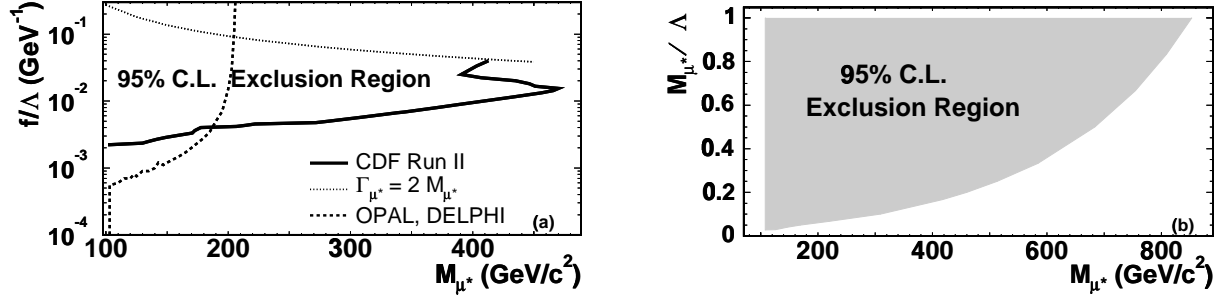


FIGURE 4. Exclusions regions for the GM (a) and CI (b) models. Also shown in (a) are the regions excluded by the OPAL and DELPHI experiments for the GM model [10].

## CONCLUSION

We have presented a search for excited and exotic muons in the  $\mu\gamma$  channel. No evidence of a  $\mu^*$  signal is found. Limits on the excited muon mass are established based on a contact interaction and a gauge-mediated model, the latter of which are the first limits at a hadron collider.

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